INTERNATIONAL STANDARD

ISO/ASTM 52939

First edition
2023-12

Additive manufacturing for construction — Qualification principles — Structural and infrastructure elements

Fabrication additive pour la construction — Principes de qualification — Éléments de structure et d'infrastructure

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Reference number
ISO/ASTM 52939:2023(E)

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Published in Switzerland

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO document should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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This document was prepared by Technical Committee ISO/TC 261, *Additive manufacturing*, in cooperation with ASTM Committee F42, *Additive Manufacturing Technologies*, on the basis of a partnership agreement between ISO and ASTM International with the aim to create a common set of ISO/ASTM standards on Additive Manufacturing and in collaboration with the European Committee for Standardization (CEN) Technical Committee CEN/TC 438, *Additive manufacturing*, in accordance with the Agreement on technical cooperation between ISO and CEN (Vienna Agreement).

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

The construction sector is increasingly facing challenges with respect to labour shortages, project delays, increased lead times, excessive material use, large amounts of waste and adverse CO_2 footprint impacts. Furthermore, from a market perspective, the global construction demand is increasing especially as the housing crisis continues and infrastructure projects (whether new or sustaining existing structures) are on the increase. Additive construction (AC) also known as additive manufacturing for construction (AMC) and 3D construction printing (3DCP) has the potential to address these issues directly.

Of late, AC has made great strides. Printed elements could potentially prove to be more durable, more sustainable, more eco-friendly, cheaper (en masse), and faster to deliver than conventional construction approaches. However, without AC standards, approval, certification, and risk mitigation are unattainable.

The purpose of this document is to outline the requirements necessary as a basis for production and delivery of high quality additively manufactured structures (residential or infrastructure) in the construction sector.

Important steps of the AC process are specified. These steps will be controlled and monitored to ensure high quality printed structures for on-site or off-site use. This document is not intended to be technology- or material-specific, and therefore sub-processes are applicable depending on the approach used. However, it should be noted that printed element(s) should be approved by a locally certified engineer and adhere to both local and regional specifications and requirements.

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Additive manufacturing for construction — Qualification principles — Structural and infrastructure elements

1 Scope

This document specifies quality assurance requirements for additive construction (AC) concerning building and construction projects in which additive manufacturing techniques are used for construction. The requirements are independent of the material(s) and process category used.

This document does not apply to metals.

This document specifies the criteria for additive construction processes, quality-relevant characteristics, and factors along AC system operations. It further specifies activities and sequences within an AC cell (additive construction site) and project.

This document applies to all additive manufacturing technologies in building and construction (load bearing and non-load bearing), structural and infrastructure building elements for residential and commercial applications and follows an approach oriented to the process.

This document does not cover environmental, health and safety aspects that apply to printing facility setup, material handling, operating of robotic equipment, and packing of equipment and/or elements for shipping but material supplier guidelines, robotic solution operating guidelines, and local and regional requirements are applicable.

This document does not cover design approvals, material properties characterization and testing.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO/ASTM 52900, *Additive manufacturing — General principles — Fundamentals and vocabulary*

ISO/ASTM 52950, *Additive manufacturing — General principles — Overview of data processing*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO/ASTM 52900 and the following apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
additive manufacturing for construction
AMC
process to join materials to make structural and non-structural elements/components and systems from 3D model data usually by depositing material layer upon layer as opposed to subtractive and formative manufacturing methodologies

3.2
additive construction
AC
term to describe all relevant disciplines and knowledge for the construction segment using additive manufacturing process categories

Note 1 to entry: The use of the technologies covers all relevant construction sectors, for example large scale real estate projects, entire buildings and building elements, civil infrastructure, and disaster relief.

Note 2 to entry: AC describes all relevant knowledge disciplines, for example: architecture, engineering, structural engineering, materials engineering, robot operator, project management, construction management, facility management, etc.

Note 3 to entry: Other terms used interchangeably are: Digital Construction (DC), Construction 4.0, Advanced Manufacturing in Construction (AMC), Construction 3D Printing (C3DP) and 3D Construction Printing (3DCP).

Note 4 to entry: Building materials include:

— cementitious variations such as concrete and mortar, polymer modified pastes,

— composite materials.

Note 5 to entry: Intrinsic to the current definition is a high degree of robotic automation, a reduced degree of human intervention during the construction process, and minimal waste due to as-needed material delivery systems.

Note 6 to entry: As of this writing in 2023, the field of AC is rapidly evolving, and novel materials and methods are very likely to become included in this definition.

Note 7 to entry: AC is used on-site or off-site (e.g. modular factory-based production).

3.3
layer deposition
application of a single layer

3.4
AC cell
printing solution deployed on site for in-situ printing (includes material mixing and placement systems)

3.5
material deposition device
numerically controlled assembly, including mixing and delivery mechanisms for raw materials, binders, and additives; places the mixture based on a digital simulation entered in the assembly's electronic programs, without the need for direct human intervention or for using moulds

3.6
physical production
physical totality of the build space, elements located on the build space, and production related support structures and plant in the build space of the system

3.7
virtual production run
computer/digital simulation of the *physical production* (3.7) run (print file)

EXAMPLE Printing simulation.

3.8
dry production run
process of running the build program with no materials to verify the first layer toolpath and other critical points of the program; and can be part of calibration process

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3.9
construction process
digital and physical AC operations, from setup of the robot through completion of the final printed element, including quality assurance testing and verification

3.10
mechanical, electrical and plumbing
MEP
building systems required for heating, ventilation, and air conditioning; electrical power and communication supply; and water supply and sewage removal, respectively

3.11
printed element
construction 3D printed component, whether constructed on-site (in-situ) or off-site, that gets incorporated into a building or structure, as a complete infrastructure component

EXAMPLE Walls, columns, beams, etc.

3.12
printability
ability of the material to be easily delivered to the print head, processed by the print head, e.g. *extrudability* (3.13), and meet consistent layer shape stability, *buildability* (3.14) requirements, and if applicable *pumpability* (3.15)

3.13
extrudability
ability of the material to smoothly be ejected through the printing nozzle without inducing any blockage of the conduits or significant damage to the material quality

3.14
buildability
ability of a print to preserve vertical and lateral stability under increasing loads coming from superposed/subsequent layers with controlled deformation

3.15
pumpability
material paste criterion that is related to the concrete extrusion and workability, as it is important to ensure that the materials have a continuous easy-flowing behaviour from the source to the printing material deposition device/nozzle

Note 1 to entry: Pumpability ensures the materials can be pumped easily and continuously without creating clogging issues inside the delivery system.

4 Constructability, assessment and review

4.1 General

The AC element requirements shall be specified and verified before the data preparation. The results shall be transferred in a definite sequence with associated production specifications including specific requirements in respect to the quality control (for load and non-load bearing elements). It is recommended that any asset monitoring and/or management be based on locally applicable standards/codes/regulations which could be based on numerical verification analysis.

If the production request is incomplete (for example missing technical drawing) or an initial commissioning is associated with restrictions, the customer shall be notified to correct the problem.

Figure 1 shows the individual steps for checking the feasibility and qualification phase as a pre-requisite for the serial production with AC.

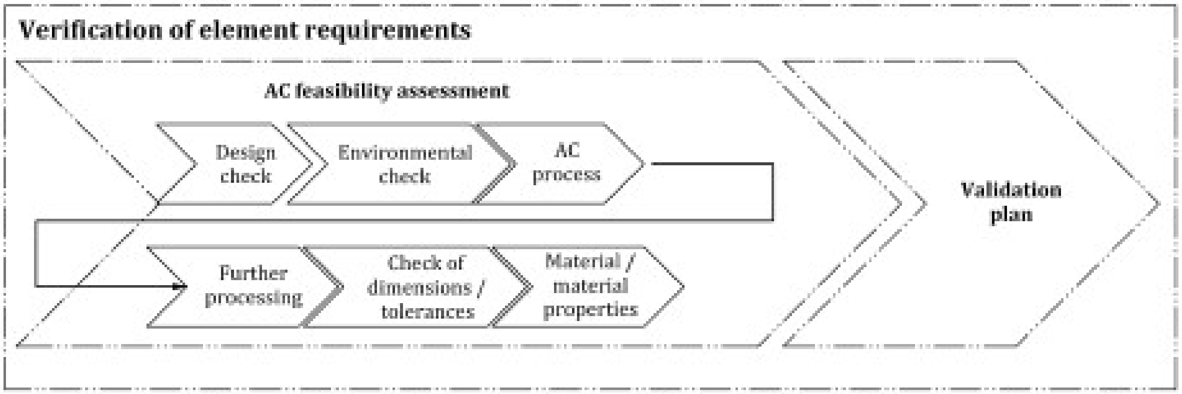

Figure 1 — Steps involved in verification of AC element requirement

4.2 AC feasibility assessment

AC feasibility, including AC element requirements, shall be evaluated by suitable personnel (e.g. technology experts or instructed persons, obtaining relevant permits from local authorities, classified and registered as required by authorities having jurisdiction and proven to have designed and accomplished successfully a specific number of 3D printed elements (e.g. 5) with the same construction process and comparable dimensions and complexity).

The necessary production competence is only available in the direct AC environment. It is important to include all element requirements in the feasibility check. The evaluation shall include the following steps:

a) **Design check**: the process-relevant design directives should be consulted to evaluate the design's AC feasibility and comply with national, regional, and local codes. In addition, process-relevant AC restrictions such as minimum wall thicknesses and reinforcement requirements shall also be taken into consideration.

b) **Environmental check**: for the environmental dimension, material selection and design stages are regarded as crucial to the sustainability performance of a built element throughout its life cycle. It is important to perform a sustainability assessment of the building material or the building product itself, in accordance with ISO 21930 and ISO 14001 following a cradle-to-grave approach of a life cycle analysis (LCA) and track macro-indicators, for both internal use and to elaborate Environmental Product Declarations (EPDs) of building products after validation. Environmental checks/studies shall be done in compliance with all national, regional, and local requirements.

   Core indicators to use are:

   — global warming potential (CO_2 equivalent emissions);

   — greenhouse gas (GHG) emissions that have a potential impact on the climate.

   Other relevant indicators can be:

   — Pollution potential: freshwater resources that have a potential impact on the depletion of freshwater resources (in case no metallic material will be used in the paste mix design, using other than freshwater, such as sea water, or treated water may be envisaged in the process, based on the usage of the printed element, and its interaction/exposure to end users).

   — Fossil fuel depletion potential (oil equivalent): consumption of non-renewable raw materials and non-renewable primary energy.

   — Ozone depletion potential (CFC-11 to air): release of gases that have a potential impact on the stratospheric ozone layer.

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— Amount of waste generated by type: total volume of non-hazardous and hazardous wastes that has a potential impact on the generation of waste for disposal

— Acidification potential (SO_2 to air) - potential impact on the acidification of land and water resources.

— Freshwater eutrophication potential (P to freshwater): potential impact on the eutrophication of water bodies.

c) **AC process**: it is also necessary for qualified engineers to check whether the desired element, and element properties to be attained, are AC feasible with the process parameters already qualified, or whether adaptations are necessary to attain AC feasibility. AC specific process category risks also need to be evaluated by qualified engineers to achieve dedicated component requirements. Refer to Table A.1 for specific processes and materials.

d) **Further processing**: if a further (semi-)automated manufacturing step occurs, it is necessary to check whether the design is appropriate for this, if auxiliaries cannot be used. If subtractive or finishing processes are then carried out to attain the required manufacturing tolerances, corresponding design details shall be provided as early as the data processing, if necessary.

e) **Check of dimensions/tolerances**: the tolerances specified in the design shall be attainable in the selected AC process. Post-treatment shall be considered before the start of the AC process.

EXAMPLE 1 Any special considerations for reinforcement and/or MEP integration, starting, stopping, or skipping in the AC process.

f) **Material/material properties**: AC feasibility shall be considered beyond the selected technology, depending on the material, material mix design, and over the entire AC process. The specified material properties shall be incorporated here. Local standard tolerances for fire resistance, load/compressive strength, tension, shrinkage, creep, and resistance to environmental effects such as moisture, cyclic freezing, and ultraviolet (UV) radiation etc. should be followed.

EXAMPLE 2 Materials that exhibit different AC constraints.

An individual element evaluation shall then be conducted to define the necessary measures for quality assurance. Based on the method for quality assurance already implemented as well as the risk analysis for the relevant application, it is necessary to check whether separate measures for element-related quality control are necessary (see 7.4).

4.3 Validation plan

The requirements of the direct manufacturing environment include the qualification plan for the series element. The prerequisite is qualification of the material for a definite AC process. A qualification plan shall be formulated for the elements and associated test methods according to the relevant work and/or procedural steps as specified by the customer. The element(s) production is validated in a stage process (see A.2 or ISO/ASTM 52901). Each phase is successfully completed upon signing by suitable personnel.

The methodical recording of the element requirements can be derived, for example, from ISO/ASTM 52901. This makes it possible to derive which validations can be necessary beyond this document.

5 Infrastructure of the AC cell

The following requirements are relevant for the infrastructure of the AC cell:

a) **Equipment:** Environmental, Health and Safety (EHS) checks and management should comply with existing local and regional statutory on-site and off-site standards for all equipment. Some examples are listed below:

— EN 12001;

— EN 12629-1;

— ISO 4413;

— ISO 4144;

— ISO 12100;

— ISO 13849-1;

— ISO 13849-2;

— ISO 13850;

— ISO 13854;

— ISO 13857;

— ISO 14118;

— ISO 14119;

— ISO 14120;

— EN 60204-1;

— ISO 10218-1;

— ISO 10218-2;

— EN 60204-1.

b) **Safety at work**: a safe working environment with consideration of the statutory regulations shall be ensured. This includes personnel instruction concerning the occupational safety measures and equipment.

The users of this document should refer to appropriate safety management guidance and local legislation and regulation to gain a full understanding of specific requirements.

The following is a summary of some of the safety management aspects AC should consider.

1) Safety legislation holds operators to account for the protection of their employees, the public and the environment in relation to their industrial activities. While legislation and regulations vary in each country or region, the basic principles of safety management are common and should be common practice for all AC companies.

2) Operators shall possess safety management arrangements that identify responsible and accountable persons within their organization. The safety management arrangements will also detail the processes in place to ensure that safety is achieved for all operations of the company and considering all hazards that are associated with AC. Safety management arrangements should be proportionate to risk and complexity of the operation.

3) The central aim of safety management is to identify all foreseeable hazards and reduce risks to a level that is tolerable and as low as reasonably practicable or achievable. Risk control measures are used to achieve this in various ways across the safety discipline.

4) As the operator of robotic AC equipment and associated machinery and materials, operator shall consider and ensure the safety of all aspects of operation including, but not limited to:

— the printing location, factory or site-based;

— the machinery being used and interfaces between machinery;

— emergency and accident arrangements and response including first aid requirements;

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— safety signage;

— safe handling and storage of materials;

— construction site safety requirements and PPE requirements;

— process warnings and cautions;

— installation and use of barriers and guards;

— adequate safety training and provision of adequate safety information;

— safety discipline and safety culture;

— duty of care for workers;

— reporting near misses;

— learning from experience;

— consideration of public safety;

— keeping auditable records for safety decisions.

c) **System installation**: the AC system shall be installed by qualified personnel (see 7.2). Evidence of installed conditions shall be documented (e.g. service report, final acceptance report, reports on modification to the system, designation of the machine type including version status of the software components and, if applicable, version status of the hardware components, machine identification number). All staff delivering the product to be deemed appropriately trained with maintained and retained record as part of a quality management system (QMS) with the process steps recorded.

d) **Maintenance**: all maintenance activities shall be completed and documented.

The machine installation and maintenance refer to systems of the process control as well as all devices relating to systems and parts [e.g. material storage, mixer, pump, UV system (if applicable)].

e) **Production environment**: system manufacturer specifications shall be adopted with respect to ambient and installation conditions.

f) **IT infrastructure**: for an AC factory setup, ensure security of the server landscape, provision of the IT hardware, safety and archiving systems, etc. (e.g. according to ISO/IEC 27001) as outlined in the following non exhaustive list shall be followed:

— floor load capacity and evenness of the ground, absence of vibration;

— extensive availability, minimum distance to neighbouring systems and equipment;

— controlled or permissible temperature, humidity, light conditions, air particle components;—

cleanliness of the AC environment;

— logged installation conditions and qualification of the production system;

— logs covering all other quality-relevant influencing factors regarding the function of a system.

The AC management system ensures that the correct steps occur in the qualified sequence with the corresponding parameters. This includes planning the machine capacity utilization and material stock corresponding to a specified minimum level. A system for planning the bottlenecks shall be demonstrated.

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6 Qualification of the additive construction process

6.1 Quality-relevant process steps within the additive construction process

It is recommended that a quality management system (e.g. ISO 9001) is in place when the AC element manufacturer applies this document. Additionally, this document can be used to establish a quality management system specifically relevant to AC technology.

In order to ensure high quality within an AC cell, the complete process chain (see 6.2 to 6.7) of the production process and personnel requirements (see 7.2) shall be considered.

The relevant areas of the process chain are shown in Figure 2. These comprise:

— Quality assurance: preventive measures that ensure the required element quality over the entire process chain (see Annex B for a proposed approach for AC quality assurance);

— Data preparation: digital processing occurring before additive construction (see A.3);

— Material management: material flows occurring before and during the printing process (see B.3);

— System related pre-processing: manual activities occurring in the immediate environment of the printing system and serving to initiate the controlling of the process (see A.3);

— Process guidance (build cycle): complete machine cycle in which elements are produced additively (see A.3);

— Default post-processing: activities occurring in the environment of the production system and performed downstream of the process control (see A.1);

— Element specific post-processing: activities on the element after the process guidance (see Annex A, Annex B and Annex C).

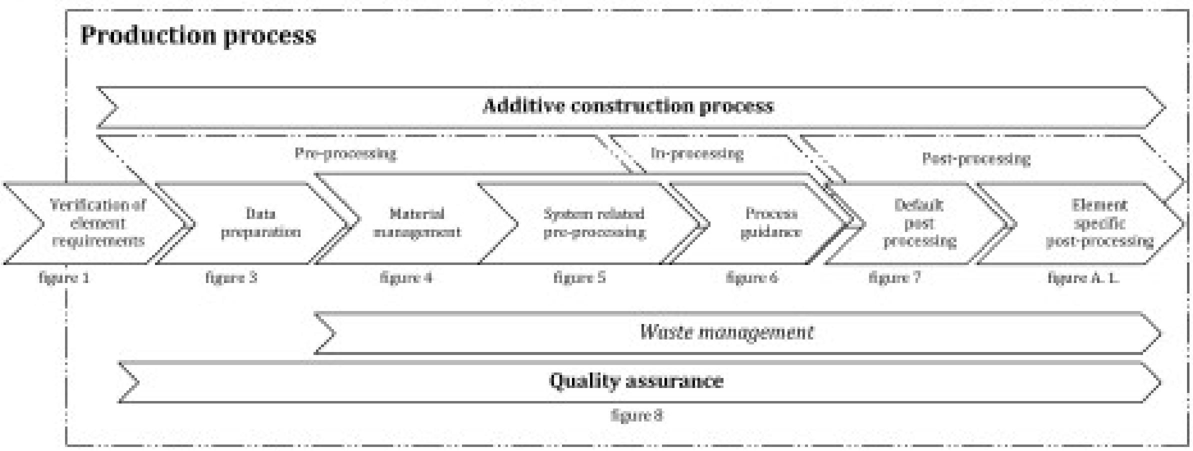

Figure 2 — Quality assured process in AC on-site or off-site

The assurance of the element quality requires comprehensive specification of the production process (Figure 2):

a) Quality-relevant characteristics as well as test methods and intervals for monitoring each individual process outlined in Figure 1 should be detailed;

b) Work equipment and any applicable ambient conditions required for and during the printing process shall be in place;

c) System-related maintenance and servicing activities; (see Table D.1 for specific process examples) should be taken into account;

d) Qualification measures for determining relevant input variables (e.g. material properties) and resultant output variables, which are derived from a combination of the previously specified characteristics over the entire process should be defined;

e) Defining the measurement, geometric dimensioning, and tolerancing regarding AC usage shall be specified by application specificity and/or based on user requirements (see Annex B).

6.2 Data preparation

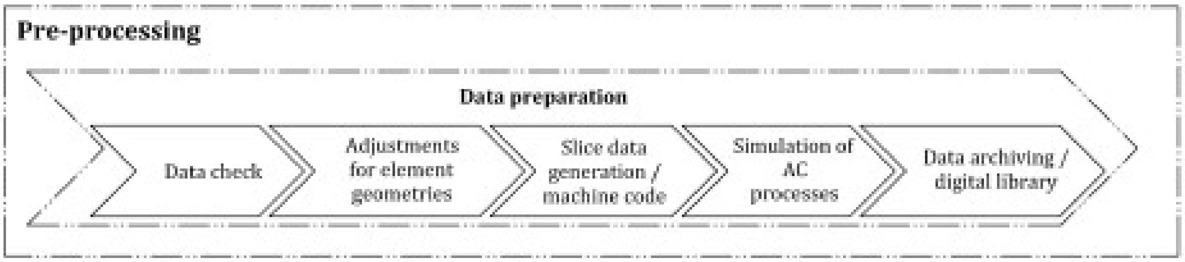

Figure 3 — Data preparation steps

Data structure principles of ISO/ASTM 52950 shall be applied. The definitions of ISO/ASTM 52900:2021, 3.4 shall be followed.

If technically applicable, the following process steps from Figure 3 shall be specified and their testing and documentation defined:

a) **Data check**: an inspection regarding error-free, process ability of the 3D data shall be completed. If errors are found, a data repair shall be carried out with close collaboration and approval of the engineering team especially if any geometric modification is required;

If applicable, documentation of the file format (e.g. STL, AMF) conversion (tessellation) parameters is required.

b) **Adjustment for element geometries**: allowances for temporary support (e.g. overhangs) and MEP integration if applicable. 3D data changes are allowed as they relate to element changes if all adaptations are documented in comprehensible and verifiable form (this requires version control of the modified data set), and proper approvals are sought and agreed upon prior to changes being made.

Slice data generation/machine code (e.g. G-code): conversion into machine-specific slice data with complete process parameters based on the approach and material.

In case of software updates, input and output data should be used to check that the generated data corresponds to the referenced output data.

The parameters for the data conversion shall be specified and complied with in the corresponding process description, under the consideration of the key quality assurance characteristics of the particular AC process category used.

c) **Simulation of additive construction process**: virtual production run to predict printability and print performance based on the geometry, material, and AC process categories/characteristics (see Table D.1 for specific examples).

Furthermore, a mock-up for a complex part of the element to be 3D printed should be constructed to demonstrate that the element is printable, and that the material is flowable, extrudable, buildable, pumpable, and that the extruded material's open time (the period of time in which the workability is consistent within certain tolerances acceptable for the process) is all as designed, to achieve required shape within allowable tolerances.

d) **Data archiving**: unique versioned archive of the production run (or for reference to as "as built/as built digital model" drawings). Archiving duration as specified for the relevant application/sector.

6.3 Requirements for the material management

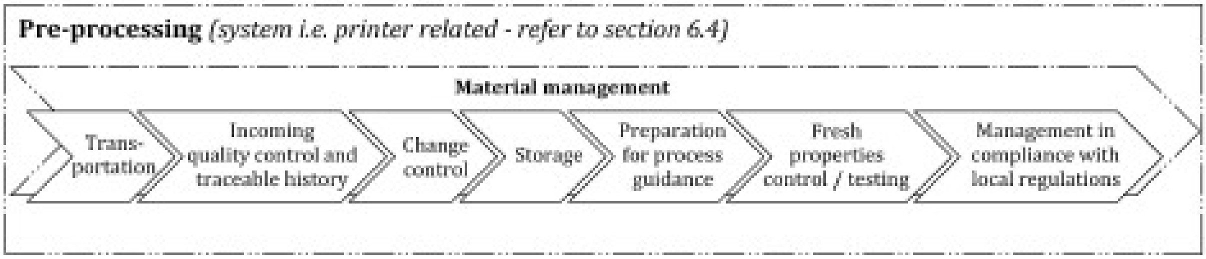

Figure 4 — Elements of material management

Special material handling considerations should be taken into account, as it is also necessary to define the specification of essential parameters and, if applicable, associated test methods, which ensure the suitability of a material and material mix design for the respective printing process. Follow local codes and regulations under the authority having jurisdiction. Figure 4 depicts the elements of material management.

Consideration should be made for any "supporting material" such as binder or glue products; for material handling (storing and mixing) and delivering (pumping and printing). Furthermore, it should be noted that printed material at the head/nozzle/extruder is different from material at the mixer/material delivery area (see Table D.1 for specific process examples).

To ensure the required properties of the material, the following process steps shall be specified, and their testing and documentation defined:

a) **Transportation:** should adhere to supplier recommendations;

b) **Incoming quality control:** labelling of incoming material with batch testing of raw material as directed by the material supplier; (see Table D.1 for specific process examples)

c) **Charge control**: a traceable material and material mix design history shall be compiled, documented, and saved;

d) **Storage**: suitable storage conditions (at least monitoring of moisture (as applicable) and temperature) should follow suppliers' recommendations. Consideration should also apply to on-site ready-mix production and delivery systems (see Annex B);

e) **Preparation for process guidance**: if applicable, adaptation of the material composition for the process control (see Annex C and Table D.1 for specific process examples);

f) **Fresh properties in-process control/testing (automatic or manual)/monitoring:** parameter control, parameter tests (example, Flow and Slump tests), and probes, can be part of the quality monitoring plan. Appropriate testing of materials and site ground conditions shall be carried out with documentation retained to ensure traceability.

g) **Management complying with local regulations:** AC technology specific, AC material specific, environmental aspects, etc.

6.4 System related pre-processing

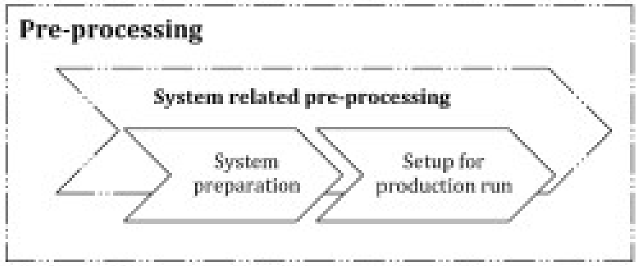

Figure 5 — Elements of system-related process preparation

If technically applicable, the following process steps (see Figure 5) shall be specified, and their testing and documentation defined:

a) **System preparation**: restoration of the initial machine state for the following production run:

1) The preparatory steps shall be followed as indicated by the manufacturer (inspection and testing procedures including those related to un-packing/setup of equipment for on-site printing if applicable). See 7.2 for personnel duties;

2) Cleaning: cleaning processes shall be carried out according to manufacturer instructions. (See Table D.1 for specific process examples).

b) **Setup for production run**:

1) slab or base for print (ensure tolerance requirements are met per printer supplier recommendations, see Table D.1 for specific process examples);

2) system and process materials, requirements for production, dry production run verification in-line with manufacturers requirements (could include verification that slab/base is level as applicable);

3) dry run material delivery system set up;

4) stop/start procedures based on material and printer specific recommendations;

5) specify build cycle parameters;

6) environmental controls;

7) hoarding, fencing, or any structures to surround and/or control access, weather, foreign deleterious materials such as dust, wind borne contaminants (leaves, grass, sands, etc.), ambient temperature and moisture, also if there are any noise abatement or controlling structures;

8) safety within the cell;

9) definition of vibration limits natural and by ambient (see Table D.1 for specific process examples);

10) recycling and waste control (ISO 21930 and ISO 14001).

6.5 Built process guidance

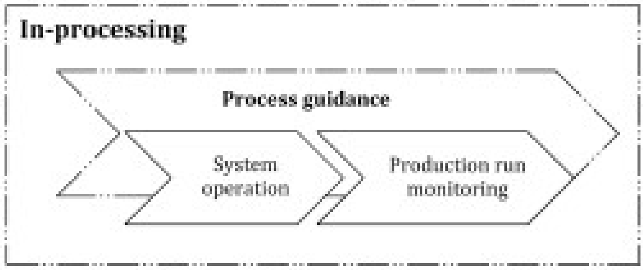

Figure 6 — Elements of the process guidance

The requirements of the printing environment include system monitoring during operation.

The following process steps (see Figure 6) shall be specified and their testing and documentation defined (see Annex C for a proposed quality assurance approach in built process guidance):

a) **System operation**: starting and executing the production run:

1) the operating steps indicated by the manufacturer shall be observed;

2) printer start: work instructions shall be followed;

3) placement of reinforcement (rebar, metal wire, etc.) should be incorporated based on the required performance tolerances;

4) MEP integration (as applicable) shall be incorporated as per the required design parameters:

— any stop/start activities for mechanical, electrical, and plumbing integration and/or reinforcement placement should follow system providers' documented practices.

5) logging the production run:

— all stop/start activities shall be documented;

— dataset of the manufacturing batch (geometry, number, layer thickness, exposure strategy, etc.);

— process parameters (e.g. feed rate, nozzle cleaning steps, material supply or layer deposition, calibration, print speed, layer time, extrusion rate; see Table D.1 for specific process examples);

— record environmental conditions during printing (e.g. ambient temperature, humidity, wind speed);

— printability can be defined by flow of material which can be measured by a power consumption of a pump;

NOTE Possibly, buildability has an extra definition status of the components (conveying rate, print head status, axis positioning, etc.);

— material and machine data (serial number, etc.).

b) **Production run monitoring:** a manual or automated monitoring plan should be in place (e.g. technology/application probe taking, start/stop document, materials content, visual inspection, NDT). This may include but is not limited to:

1) collecting material sample (manually, semi-automated, automated; see Table D.1 for specific process examples);

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2) recording and evaluation of the production run via imaging methods: the recorded data enable the analysis of errors or the tracing of part defects to process deviations (one-dimensional time of flight distance measurement sensor, with a defined accuracy depending on the printed element dimensions (for example 1 mm), may be used and attached to the nozzle, to measure the distance between the nozzle to the substrate. The measurement data can be continuously transmitted back to the control system which adjusts the nozzle position accordingly. The nozzle sensor can also measure the dimensions of the printed filament. The print quality may be determined through an algorithm which measures the width of the extruded filament and compares it with the target filament width to detect over-extrusion or under-extrusion conditions. The used feedback control system should be able to automatically adjusts the material deposition rate in order to achieve the desired dimensions of the printed layer);

3) layer error analysis (partially real time-controlled) to detect an irregular material placement on the build surface (after each layer) can be integrated in the quality assurance;

4) layer defect analysis needs to be performed and in compliance with well-defined specifications;

5) interlayer time gap is measured according to defined specifications;

6) interval of height/time is measured according to defined specifications;

7) design specifications like wall tie, reinforcement shall be monitored;

8) verification of the printed layer shall be free of surface defects including any discontinuity due to excessive stiffness and inadequate cohesion between successive layers;

9) dimension conformity and dimension consistency per material being used and conducted by certified operator. This is done by the print layer and below factors that might influence print quality and should be measured, for example

   — climatic conditions (temperature, humidity, wind) on site with the printed element;

   — positioning of temperature reading equipment to be able to measure the environment and material;

   — amount and temperature of liquid and dry components;

   — temperature of end component as placed;

   — speed of mixer, pump, robot;

   — electric power consumption of the electric motors;

   — amount of additives mixed with material.

6.6 System (default) post-processing

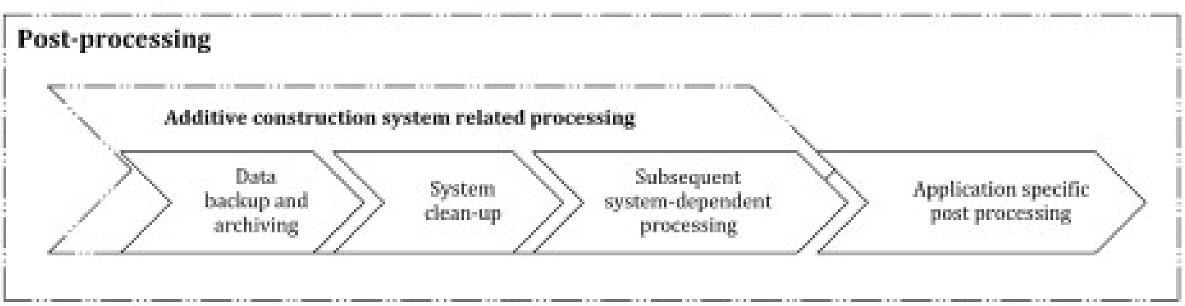

Figure 7 — Elements of system required (default) post-processing

Post-processing measures (see Figure 7) shall be designed uniformly and integrated in the qualification (see 6.7). Applied processes shall be assigned uniquely to the structure and archived for evidence records. The following process steps shall be specified and executed in a controlled manner, and their testing and documentation defined:

a) **Data backup and archiving**: backup of the logs/recording data after completion of the production run;

b) **System clean-up**: restoration of the initial state of the machine for the following production run (see 6.4 and Table D.1 for specific process examples);

c) **Subsequent system-dependent processing** to prepare for next production run;

d) **Curing environment** that should follow material supplier recommendations;

e) **Application specific post-processing**: this document does not claim to stipulate all specifications or recommendations for printed element post-processing (e.g. smoothing of surfaces either automatically or manually), but instead serves a purely informative allocation (see A.1) of the printing processes. The methods normally applied in the final processing including shipment are largely standardized. The corresponding normative documents are applicable, see Table D.1 in Annex D for specific process examples.

As a result, this document can therefore be used as a basis for the additive construction-specific process and extended with any qualification standard for subsequent steps. The quality assurance shall be implemented over the entire construction process.

6.7 Process qualification

The main aim of the process qualification of the AC process is to define reproducible, product-related indicators. This includes the testing of reference samples to a statistically significant extent, which have passed through the process chain to be qualified. The process qualification of the AC process thus forms the basis for both the identification of reproducible parameters as well as evaluation of the current process quality as defined by the ongoing quality assurance. The samples accompanying production not only serve the quantitative determination of material characteristics but rather are adopted for a qualitative comparison with a tolerance band determined beforehand based on the location and dispersion parameters of the material characteristics, to verify reproducibility of the process results.

The process steps defined in 6.1 to 6.7 shall be specified in succession and their testing and documentation defined. The defined documentation should be available for all AC relevant workers at the construction site. This typically includes:

a) **Parameter set**: the process parameters selected for the qualification shall be defined, designated uniquely, and documented. Changes to the process parameters require a requalification;

b) **Characteristic values/test specimens**: if characteristic values of the conventional material are specified in standards, these characteristic values shall be determined according to the normative requirements based on test specimens;

c) **Number of samples/production runs**: the number of specimens and production runs shall be selected in a statistically relevant manner and should be aligned with the built process monitoring solutions;

d) **Positioning/alignment**: the arrangement and orientation of the test samples shall be chosen appropriately corresponding to the circumstances of the AC-system and the scope of the application (for example the z-height probes);

e) **Data communication**: a qualification of the data processing shall be carried out in case of data transfer over several software programs.

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7 Quality assurance

7.1 General

Quality assurance of the entire AC process considers all of the elements depicted in Figure 8. Consideration for on-site production, off-site production and delivery, and on or off-site testing shall be taken into consideration when determining quality assurance.

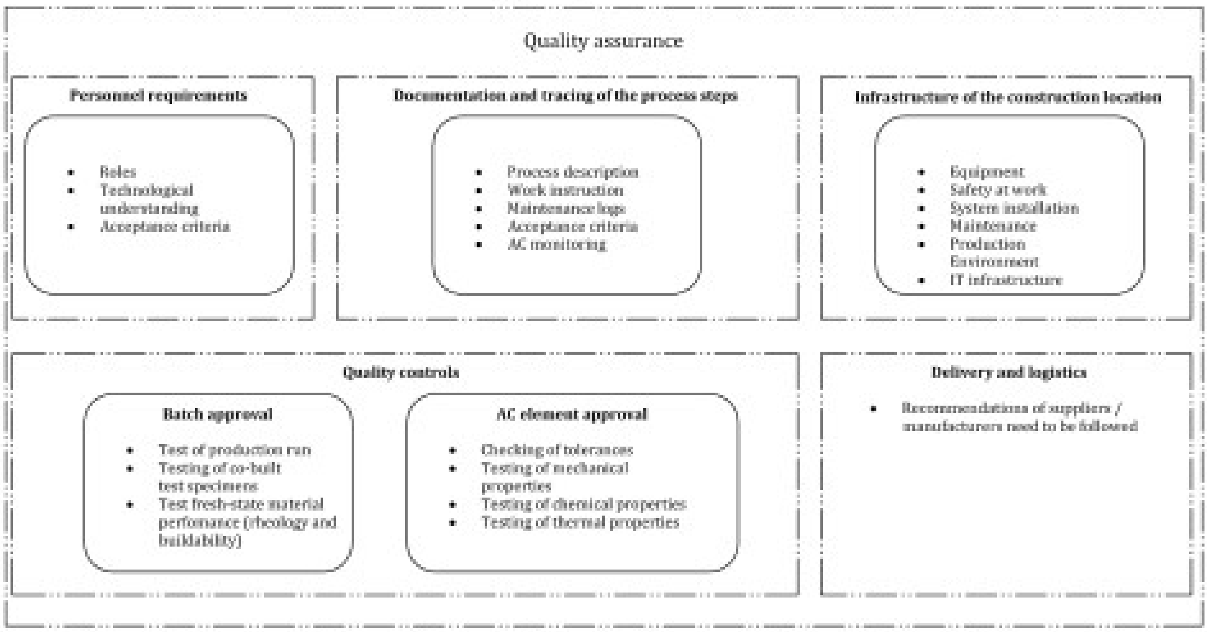

Figure 8 — Quality assurance elements

7.2 Personnel requirements

Personnel roles shall be well defined and documented for all areas of the AC. Personnel shall be qualified corresponding to their task. Qualification records shall be kept for all AC personnel.

Roles along the additive process chain are:

a) CAD, CAM, and CAE engineers;

b) civil, structural, material, and mechanical engineers with AC knowledge;

c) machine operators;

d) tradespeople;

e) test personnel (for non-destructive testing);

f) AC Quality Assurance specialist who will be responsible to fulfil the standard's requirements;

g) health and safety officer (shared or dedicated responsibility).

The responsibilities of these roles include maintenance of the systems, implementation and compliance with the work safety precautions, process qualification and internal (or external) inspection of the required quality records in one or more randomly selected job audits.

The documentation check should be conducted with demonstrable technological understanding referring to AC process specific requirements. This includes knowledge about currently available AC

and construction standards along with sound expertise of the relevant process category and its quality assurance aspects.

NOTE The scope of the documentation check includes the inspection of the digital and physical production steps.

Acceptance criteria in relation to technology and material specific criteria – shall be defined by suitable technical staff as part of the quality assurance aspects listed in Clause 4.

7.3 Documentation and tracing of the process steps

Documentation of the AC process and process steps is necessary to verify quality assured processes. The requirements for the direct AC environment include the following production-requisite specifications:

a) **Process description**: description of all relevant processes along the production process chain (see Figure 2).

b) **Work instruction**: procedure for carrying out the relevant manual activity at the respective stations. Steps that are prone to error and critical to quality shall be emphasized including the corresponding characteristics.

   EXAMPLE 1 Cleaning the system(s).

   EXAMPLE 2 Documentation of the versioned, qualified machine parameters per executed production run.

c) **Maintenance logs**: maintenance processes and intervals as well as machine calibration.

   Regular measurement of the components with a direct influence on the printing process (e.g. printing machine speed, calibration of the feeding rates of the print head) in a manner and intervals suitable for the application.

   Cleaning work shall be carried out in accordance with specific system maintenance plans. Maintenance and repair activities shall be carried out for the machine type in use in accordance with manufacturer specifications regarding inspection and maintenance. This applies to both the frequency of the maintenance work to be carried out as well as the responsibilities for the necessary activities. Typically, daily, weekly and monthly maintenance and repair work accompanying the build job shall be carried out by the owner/operator of the AC system, whose implementation is to be verified in a suitable manner.

d) **Acceptance criteria**: defined and referenced methodology to evaluate the implemented sub-process. The individual control points along the entire process chain require a decision-making basis. This shall be known and easily accessible to the personnel:

   1) Test equipment compatibility shall be verified;

   2) Documentation regarding production of the samples accompanying production; test reports; error report;

   3) Documented proof regarding the quality of the material;

   4) Recording the characteristic values of each machine per production run; system-related pre/post-processing; process data recording; log of the installation qualification, acceptance of the AC system by the manufacturer;

   5) Inspection of the process results for reproducibility by analyses: regular monitoring of the error rates or process deviations pointing to a corrective measure (see Table D.1 for specific process examples)

6) A generic process ensuring compliance with required part specifications shall be provided.

e) **AC monitoring**: documentation obligation for the individual processes carried out (e.g. job card system) in order to ensure traceability of the production steps per element; data processing; post-processing steps relating to the system and element;

1) For example part file, signed route sheet, checklist, personnel qualification.

2) Check of AC feasibility (see 4.2);

3) Order processing: complete order processing includes, in particular, the specification of element-related quality criteria and their testing;

4) Repair: a process for remedying part errors shall be defined.

7.4 Quality controls

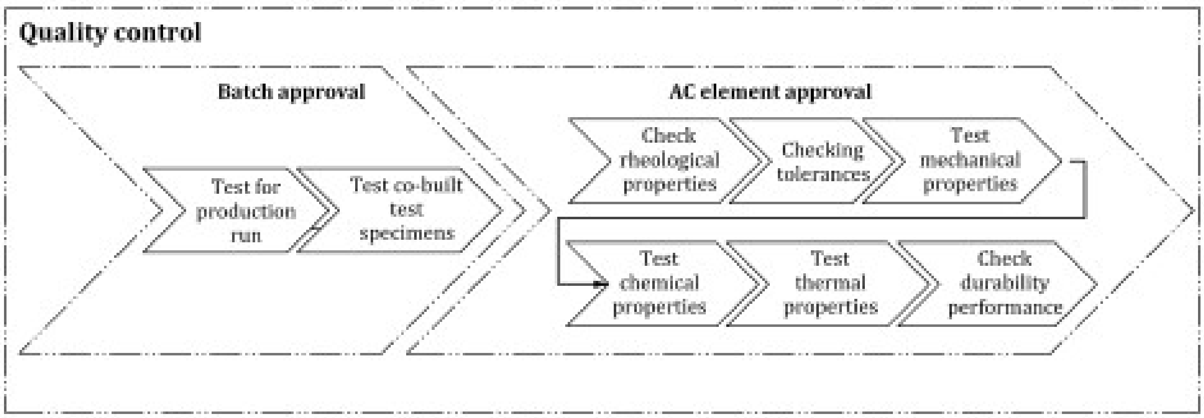

Figure 9 — Elements of quality control

Process-relevant tests shall be conducted as part of the manufacturing process. The approval procedure for a production run shall be specified and corresponding tests and documentation shall be defined.

The AC element's quality shall be verified by means of a comprehensive process documentation. All specified as well as quality-relevant characteristics and process steps carried out shall be complied with and documented (see Figure 9 and Figure 10).

The result of the visual inspection shall be documented in photographic form in the test report.

Samples accompanying production can be used to derive statements on expected mechanical-technological properties (density, porosity, hardness, static strength and further tests building on this such as dynamic part behaviour).

After the production run, it is necessary to determine (based on a visual check and available process logs) whether faults or errors have occurred in the process.

EXAMPLE Visual inspection, in particular comparison with technique-specific errors (displacement, defect, crack, etc.) according to the specified quality characteristics or acceptance criteria, see 7.3.

a) **Test for production run:** if the values are within the permissible range defined in the qualification, the production run can be approved. This comparison forms the basis for measuring the process quality and expected element quality. If the material characteristics of the co-built test specimens are outside the intervention and warning limits, the production run is first regarded as a rejection. The customer shall be informed about this in writing. Such a deviation shall also be documented in the fault log. Defective elements shall be marked accordingly as rejects and, if the error cannot be remedied, disposed of.

b) **Testing of co-built test specimens**: an indication for high process stability beyond the log data is provided via co-built test specimens. Depending on the requirements of the relevant industry or respective application, the density, porosity, hardness, strength, dimensional accuracy or possible anisotropy of the elements (see ISO/ASTM 52902) can be monitored.

Samples accompanying production serve for unique traceability per production run in the event that further destructive and non-destructive tests have to be carried out (static/dynamic load, etc.) in order to gain additional insights. The samples accompanying production including the associated documentation shall be archived according to the requirements of the relevant industry or relevant application.

c) **AC element approval:** The element is approved according to the previously defined validation plan (see 4.3). Figure 10 shows complementary measures for quality control.

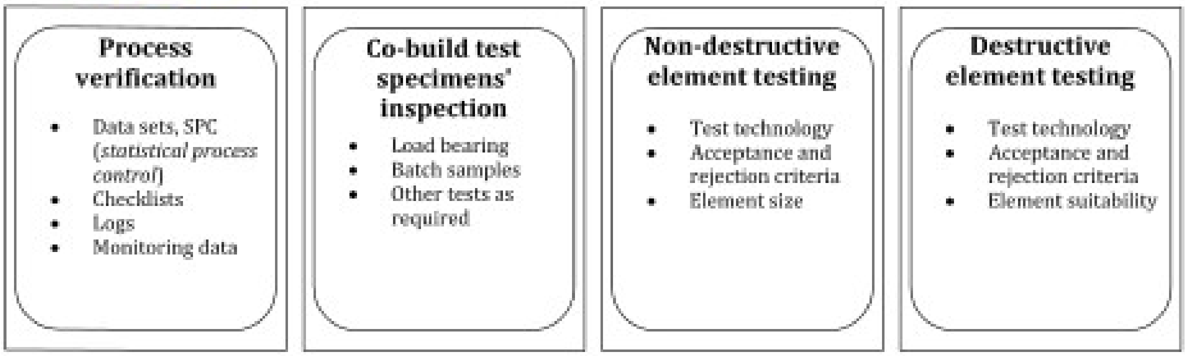

Figure 10 — Approaches to quality control

This document examines those of the process testing exclusively, whereby this represents a basic prerequisite for a random sample inspection of series elements. An example overview of the separate individual and/or random testing can be found in A.1.2 and A.3. Further areas include the following:

— check rheological properties of material for intended application;

— check tolerances;

— test mechanical properties;

— test chemical properties;

— test thermal properties;

— check durability performance.

7.5 Delivery and logistics

Recommendations of suppliers/manufacturers shall be followed.

Annex A
(informative)

Supplementary information

A.1 AC Element specific post-processing

A.1.1 AC structure-related final processing

As for the process itself, the reworking shall also permit referencing. The following shall be provided as a minimum:

— job cards;

— process descriptions and work instructions for the relevant post-processing stations;

— documentation of the personnel qualifications.

Post processing can be needed due to element specifications that cannot easily be attained with the selected AC technology.

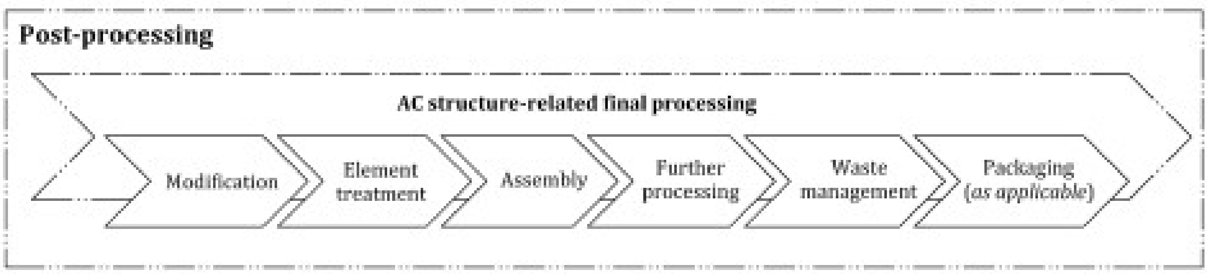

Figure A.1 — Requirement for element specific post-processing

Possible post-processing steps are illustrated in Figure A.1 and below:

a) **Modification**: elements needing to be sculpted with holes (for electrical conduits) or post-drilled for mechanical fixings (e.g. steel balustrade);

b) **Element treatment**: dyeing, grinding, blasting, galvanizing, painting, etc.;

c) **Assembly**: (e.g. multiple sections for a bridge structure);

d) **Further processing** (as applicable): MEP integration and placement of insulation, etc.;

e) **Packaging** of AC element(s) (as applicable) in preparation for shipping and delivery to end customer;

f) **Waste management/disposal** of excess material may be key due to one or more of the post processing steps above.

Follow local codes and regulations for post-processing steps compliant with the materials being used.

A.1.2 AC Element testing (separate individual or random sample testing)

— inspection for dimensional accuracy: optical, tactile etc.;

— testing the structural properties: non-destructive, destructive;

— chemical analyses;

— thermal analyses;

— etc.

A.2 Example of series qualification

— printing and approving of a test sample: key factors to ensure pass/fail;

— printing and approving of production sample: key factors to ensure pass/fail and potential rework.

A.3 Overview: standards framework for AC centres (on/off site)

Standards are arranged thematically in Table A.2, whereas AC technology and material legends are listed in Table A.1. This overview will help when implementing the quality assurance measures per topic field within the AC centre (or off-site printing). There is no need for a division into individual AC technologies.

Table A.1 — AC technology and material legends (including but not limited to)

AC process categories	Material legend
BJT (Binder jetting examples SBA and SBI) – RILEM only addresses cement-based materials — SBA = Selective Binder Activation (*SCA – Selective Cement Activation- is specific to cement*; water spayed on a particle-bed of cement and aggregates/ particles) — SBI = Selective Binder Injection – (SPI) Selective Paste Intrusion - (cement paste deposited on a particle-bed mainly without binder) MEX = Material Extrusion SLA = Stereolithography MJT = Material Jetting (e.g. Shotcrete)	Ce = Cement-based material (mortar, paste, concrete) Po = Polymer-based materials (composites or concrete) Cl = Clay (sensitive to moisture content) Re = Raw earth (used as part of a mixture, similar to cob; Cl and Re are very similar) Gp = Geopolymer (could be tested the same way as concrete/ cementitious materials; chemical bonding/polymerization) The standards are not specific to these materials, but they could be used for equivalencies. Knowing how geopolymers measure up to concrete is still very useful.

The following are examples of technologies that can be used under process legend:

— parallel robotic manipulators: Delta robots, Cartesian. Gantry, Cartesian. Transforming (telescopic) gantry Stewart platforms;

— serial robotic manipulators: scara robots, cylindrical robots, cylindrical (telescopic) robots, articulated robotic.

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Table A.2 — Standards framework for AC centers on/off site

			Process legend					Material				
Topic field	Terms/ keyword	Standards	BJT		MEX	SLA	MJT	Ce	Po	Cl	Re	Gp
			SBA	SBI								
Data processing	Element definition (depending on the considered type of cement)	EN 197-1	X				X	X		X	X	X
		ASTM C10/C10M	X				X	X		X	X	X
		ASTM C150/C150M	X				X	X		X	X	X
		ASTM C595/C595M	X				X	X		X	X	X
		EN 197-4	X				X	X		X	X	X
		ASTM C989/C989M	X				X	X		X	X	X
	Tool path (G-Code) verification (without loading material)	ASTM E2853-12:2021, 1.2	X	X	X	X	X	X	X	X	X	X
	Element definition: (definitions and classification of other ingredients)	ISO 19595	X	X	X			X		X	X	X
		ASTM C33/C33M, EN 1220	X	X	X		X	X		X	X	X
		ASTM C1116/C1116M	X	X	X		X	X		X	X	X
		ASTM C330/C330M, EN 13055	X	X	X		X	X				
		ASTM C618, EN 450-1	X	X	X		X	X		X	X	X
		EN 934-2, ASTM C494/C494M (based on admixture), ASTM 260/260M (air-entraining admixture)	X	X	X		X	X				
		EN 1008, ASTM C1602/C1602M	X	X	X		X	X				
		Optional reference: Zhang, Duo, et al. "Discontinuous micro-fibers as intrinsic reinforcement for ductile Engineered Cementitious Composites (ECC)." Composites Part B: Engineering 184 (2020): 107741.	X	X	X			X				
Production environment	Setup of on-site/ in-situ and off-site production facility (logistics, installation, and testing of all equipment)	Follow manufacturers' guidelines	X	X	X	X	X	X	X	X	X	X
	Material handling (depending on the considered type of cement)	EN 197-1	X	X	X		X	X				
		ASTM C10/C10M	X	X	X		X	X				
		ASTM C150/C150M	X	X	X		X	X				
		ASTM C595/C595M	X	X	X		X	X				
		EN 197-4	X	X	X		X	X				
		ASTM C989/C989M	X	X	X		X	X				

NOTE 1 Include technology specific approaches, refer to Table A.1 for AC technology and material legends.

NOTE 2 See Annex B.

Table A.2 *(continued)*

Topic field	Terms/ keyword	Standards	Process legend					Material				
			BJT		MEX	SLA	MJT	Ce	Po	Cl	Re	Gp
			SBA	SBI								
	Waste management	ISO 14001	X	X	X	X	X	X	X	X	X	X
		ASTM E2365	X	X	X	X	X	X	X	X	X	X
		Follow local project and authority guidelines	X	X	X	X	X	X	X	X	X	X
	Air Pollution Control (DAPC)	SR814.318.142.1	X	X	X	X	X	X	X	X	X	X
AC process	Hardware	Follow manufacturers' guidelines										
	On-site hoisting and assembly	Follow manufacturers' guidelines										
	Premix characterization - Sieve analysis (including in-situ batch mixing)	ASTM C136/C136M	X	X	X		X			X	X	X
	Premix characterization – Flow (including batch/ready mixed concrete/ mortar)	ASTM C1437, ASTM C1611/C1611M	X	X	X		X	X				
		Optional reference: F.P. Bos et. al. "The realities of additively manufactured concrete structures in practice"	X				X	X				
		Optional reference: A.S.J. Suiker et. al. "Elastic buckling and plastic collapse during 3D concrete printing"	X				X	X				
AC process	Physical properties - pulse velocity	ASTM C597	X	X	X		X					
	Fresh properties - standard tests	Optional reference: Schwartzentruber, A. Catherine, C. (2012) "La méthode du mortier de béton équivalent (MBE)—Un nouvel outil d'aide à la formulation des bétons adjuvantés ",33(8):475-482	X	X	X		X	X				
		ASTM C143/C143M (hydraulic cement concrete), ASTM C1611/C1611M (Self-consolidating concrete) slump	X	X	X		X	X		X	X	X
		Optional reference: Brandy Diggs McGee and Eric Kreiger "Using Isolated Temporal Analysis to Aid in the Assessment of Structural Element Quality for Additive Construction"	X	X	X		X	X		X	X	X
		ASTM C138 / C138M density	X	X	X		X	X				
		ASTM C231/C231M air content	X	X	X		X	X				
		ASTM C1064 / C1064M temperature	X	X	X		X	X				
AC process	Production monitoring Calibration requirements System fault monitoring (material flow nozzle)	EN 206	X	X	X		X	X		X	X	X

NOTE 1 Include technology specific approaches, refer to Table A.1 for AC technology and material legends.

NOTE 2 See Annex B.

Table A.2 *(continued)*

Topic field	Terms/ keyword	Standards	Process legend					Material				
			BJT		MEX	SLA	MJT	Ce	Po	Cl	Re	Gp
			SBA	SBI								
	Material Science and Manufacturing, NDT.	ISO 1920-7, ASTM C805/C805M	X	X	X		X	X		X	X	X
		ASTM E3100	X	X	X		X	X				
		ISO 16836	X	X	X		X	X				
		ISO 16838	X	X	X		X	X				
	Evaluation of characteristic and design values for material	EN 1990:2002 Annex D	X	X	X		X	X				
	Testing hardened concrete - Part 9: Freeze-thaw resistance with de-icing salts	CEN/TS 12390-9 DIN SPEC 91167: Part 1 of 13. ASTM C666/C666M	X	X	X		X	X				
		EN 12390-1, ASTM C490/C490M, ASTM C157/C157M	X	X	X		X	X				
		EN 12390-3, ASTM C39/C39M	X	X	X		X	X				
	(based on test method and whether the concrete is fiber reinforced or not)	EN 12390-5, ASTM C293/C293M, ASTM C78/C78M, ASTM C1609/C1609M	X	X	X		X	X				
		EN 12390-6, ASTM C496/C496M	X	X	X		X	X				
		EN 12390-13, ISO 1920-4	X	X	X		X	X				
		ZTV-ING 2019/04 - Part 3 – Clause 4, Adhesive tensile strength, Layer bonding, ASTMC633, ASTMC1583/C1583M	X	X	X		X	X				
		EN 196-1, ASTM C109/C109M, ASTM C349	X	X	X		X	X				
	Masonry	EN 1052-1, ASTM C1314	X	X	X		X	X				
	Masonry	EN 1052-2, ASTM C1072, ASTM E518/E518M	X	X	X		X	X				
	Concrete properties	EN 206, ASTM C94/C94M, ASTM C1116/C1116M	X	X	X		X	X				
	Basis of structural design	SIA 260, ACI 318	X	X	X	X	X	X	X	X	X	X
	Dimensional tolerances in construction - terms, principles and application rules	SIA 414/1, ACI 117	X	X	X	X	X	X	X	X	X	X
	Dimensional tolerances in building construction	SIA 414/2	X	X	X	X	X	X	X	X	X	X

NOTE 1 Include technology specific approaches, refer to Table A.1 for AC technology and material legends.

NOTE 2 See Annex B.

Table A.2 *(continued)*

			Process legend					Material				
Topic field	Terms/ keyword	Standards	BJT		MEX	SLA	MJT	Ce	Po	Cl	Re	Gp
			SBA	SBI								
	Test methods for determining the izod pendulum impact resistance of plastics	ASTM D256			X				X			
	Test method for tensile properties of plastics	ASTM D638, ASTM D3039/D3039M (for polymer matrix composite materials)			X				X			
	Test method for shear strength of plastics by the Punch Shear Method	ASTM D732			X				X			
	Test method for shear properties of composite materials by the Short-Beam Method	ASTM D3165			X				X			
	Test method for shear properties of composite materials by the V-notched Beam Method	ASTM D5379			X				X			
	Material ultra-violet weathering effect, including changes in tensile strength, elongation, or break	ASTM D4329, ASTM 5208 (for plastics)			X				X			
	Chemical and weather resistance of material	ASTM D543, DELPHI DX900018, ISO 11403-3			X				X			
	Fire resistance and density of smoke from burning plastics	ASTM D635, ASTM D2843			X				X			
	Test method for surface burning characteristics of building materials	ASTM E84/UL 723	X	X	X	X	X	X	X	X	X	X
	Test method for determining rate of air leakage	ASTM E283/E283M	X	X	X	X	X	X	X	X	X	x
	Test method for water penetration	ASTM E331	X	X	X	X	X	X	X	X	X	X
	Outline of investigation for building construction parts	UL 3401 IRC – Appendix AW 3D-printed building construction			X			X	X			
	Test method for compressive properties of rigid plastics	ASTM D695, ASTM D3410/D3410M (for polymer matrix composite materials)			X				X			
NOTE 1 Include technology specific approaches, refer to Table A.1 for AC technology and material legends.												
NOTE 2 See Annex B.												

Table A.2 *(continued)*

			Process legend					Material				
Topic field	Terms/ keyword	Standards	BJT		MEX	SLA	MJT	Ce	Po	Cl	Re	Gp
			SBA	SBI								
	Standard test methods for flexural properties of unreinforced and reinforced plastics and electrical insulating materials	ASTM D790			X				X			
	Standard test method for water absorption of plastics	ASTM D570			X				X			
	Standard test methods for fire tests of building construction and materials	ASTM E119, UL 263			X				X	X	X	X
	Structural requirements	EC2: EN 1992-1-1, ACI 318	X	X	X		X	X				X
	Fire resistance	EN 1992-1-2, ACI 216	X	X	X		X	X				X
	Standard test methods for water vapor transmission of materials	ASTM E96/E96M			X				X	X	X	X
	Compressive strength	EN 1052-1, ASTM C1314	X	X	X			X		X	X	X
		EN 12350-1, ASTM C109/C109M	X	X	X			X				
		EN 12390-1, ASTM C490/C490M, ASTM C157/C157M	X	X	X			X				
		EN 12390-2, ASTM C31/C31M	X	X	X			X				
		EN 12390-3, ASTM C39/C39M	X	X	X		X	X				
		EN 12350-2, ASTM C143/C143M	X	X	X			X				
	Tensile bond strength between layers	ASTM C1583/C1583M (modified)	X	X	X		X	X		X	X	X
	Mechanical properties - Compressive strength	ASTM C109/C109M	X	X	X		X	X				X
		Optional reference: Viktor Mechtcherine et. al. "A roadmap for quality control of hardening and hardened printed concrete"	X	X	X		X	X				
		Optional reference: Samuel Stidwell and Eric Kreiger "Determination of Mechanical Properties of Additively Constructed Concrete Based on Specimen Orientation"	X	X	X		X	X				
	Mechanical properties - Splitting tensile strength	ASTM C496/C496M	X	X	X		X	X				X

NOTE 1 Include technology specific approaches, refer to Table A.1 for AC technology and material legends.

NOTE 2 See Annex B.

Table A.2 *(continued)*

Topic field	Terms/ keyword	Standards	Process legend					Material				
			BJT		MEX	SLA	MJT	Ce	Po	Cl	Re	Gp
			SBA	SBI								
	Mechanical properties - Three-point flexural strength	ASTM C348	X	X	X		X	X				X
	Mechanical properties - Four-point flexural strength	ASTM C78/C78M	X	X	X		X	X				
	Flexion test	ASTM C1072, EN 1052-2			X			X				
	(Depending on the test method and whether the concrete is fiber reinforced or not)	EN 12390-5, ASTM C293/293M, ASTM C78/C78M, ASTM C1609/C1609M			X			X				
	Shear test	ASTM E519/E519M, EN 1052-3			X			X				
	Modulus of elasticity	EN 12390-13, ISO 1920, ASTM C469/C469M			X			X				X
	Density	EN 12390-7, ASTM C567/C567M			X			X				
	Water absorber	ASTM C1585, EN 13369:2018, Annex F	X	X	X		X	X				
	Load bearing and tensile strength, etc. (Destructive and non-destructive testing)	Compressive strength of cast sample and of printed material sample (ASTM C31/C31M)	X	X	X		X	X				
	Standard test methods of conducting strength tests of panels for building construction	ASTM E72, EC 6 - Mansory	X	X	X		X	X				X
		BS 8500, EN 206, ASTM C94/C94M, ASTM C1116/C1116M	X	X	X		X	X				
	Concrete bridges	EN 1992-2, ACI 343, AASHTO LRFD Bridge Design Specifications	X	X	X		X	X				
		Fib Model Code 2010	X	X	X		X	X				
		EC6 – Mansory, ACI 530/530.1, TMS 402/602	X		X			X				
	Assessment of in-situ compressive strength in structures and precast concrete components	EN 13791, ASTM C42/C42M, ASTM C805/C805M	X	X	X		X	X				
	Compressive strength of cylindrical concrete specimens	ASTM C39/C39M	X	X	X		X	X				X
	Durability properties - Chloride ion penetration	ASTM C1202	X	X	X		X	X				

NOTE 1 Include technology specific approaches, refer to Table A.1 for AC technology and material legends.

NOTE 2 See Annex B.

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Table A.2 *(continued)*

			Process legend					Material				
Topic field	Terms/ keyword	Standards	BJT		MEX	SLA	MJT	Ce	Po	Cl	Re	Gp
			SBA	SBI								
	Durability properties - Density, absorption, and voids	ASTM C642	X	X	X		X	X				X
	Durability properties - Drying shrinkage	ASTM C596	X	X	X		X	X		X	X	
	Durability properties - Thermal conductivity	ASTM D5334	X	X	X		X	X		X	X	X
		ASTM C1363	X	X	X		X	X		X	X	X
	Freeze/thaw performance	ASTM C666/C666M	X	X	X		X	X		X	X	X
	Water permeability	ASTM E514/E514M	X	X	X		X	X		X	X	X
	Microstructural properties - Scanning electron microscope (SEM) and energy-dispersive X-ray spectroscopy (EDS)	ASTM C1723	X	X	X		X	X				X

NOTE 1 Include technology specific approaches, refer to Table A.1 for AC technology and material legends.

NOTE 2 See Annex B.

A.4 Notes on process deviations

A.4.1 General

The search for the root cause of the error is difficult owing to many influencing factors. A rigorous categorization of the error records is therefore recommended.

A.4.2 Appearance on the AC element

Deformation, displacement, surface errors, etc.

Annex B
(informative)

Examples for AC quality assurance

B.1 General

The contents are presented as a proposed approach for quality assurance and should not be seen as a complete or comprehensive procedure.

B.2 Data preparation

a) Utilize 3D CAD files to create the 3D structure. This is the baseline for quality checking against local and/or global tolerances.

b) Convert the 3D CAD file into an additive construction digital design. Specifically noting the number of printed layers, and layer thickness, centre lines, detailing for joins and base of the structure.

   1) Utilize the 3D CAD files to design the 3D structure.

   2) Convert the 3D CAD files into an AC digital design following the established quality requirements.

   3) Ensure the conformance of AC digital design with established requirements for the safety standards, legislation and regulations.

c) Cross reference with local and/or global tolerances to ensure that the new 3D design performance comply with safety standards, legislation and regulations.

B.3 Data storage and quality assurance

Refer to 6.2.

B.4 Material management

a) Prior to any application, all materials should be checked if they are conforming to the requirements/specifications for their intended applications. This shall be done through a quality control process.

b) Raw material shall be properly stored in their appropriate/suitable places and labelled as appropriate.

c) Materials shall be kept away from humidity.

d) All material shall be stored at a temperature ranging between 5 °C to 30 °C ideally.

e) Safety data sheets (SDS) (and ideally technical data sheets (TDS) also) are required for all materials.

f) Additives mixed with material should also follow the above guidelines.

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B.5 Mix design preparation, material mix characteristics, and trial mix requirements

a) Prepare design mixtures for each type and strength of material, proportioned based on laboratory trial mixture and field test data, to make a material mix that has a specific performance in the fresh and hardened state so as to satisfy the requirement of application.

   Ensure the required flowability, extrudability, pumpability, printability, buildability, and open time, depending on the properties of the 3D printer to be used and the objects to be printed.

   Ensure required nozzle diameter, pumping distance, width and height of printed filament, grade and type of material, ambient temperature at application time, and other AC parameters such as deposition distance, extrusion speed, and printing speed.

   Ensure printing procedures such as loading of printing material and design of printing paths align with local regulatory/country requirements.

   Use a qualified testing agency for preparing and reporting proposed mixture designs, based on laboratory trial mixtures using equipment similar to the ones that will be used in the construction, and ambient conditions similar to the application conditions.

b) The material mix shall be designed to meet certain vital criteria that have a direct relationship with the methodology of printing the material. Thus, it is critical to ensure a complementary connection between the designs of the mix and the 3D printer. In order to design the optimal mix, certain targets are to be set for the mix:

   1) maximize compressive strength;

   2) maximize workability;

   3) maximize flowability in the system;

   4) maximize buildability upon extrusion;

   5) maximize speed of material setting;

   6) maintain appropriate setting rate to ensure bonding with the subsequent layer.

c) It should be noted that among the properties of material mix design, extrudability and buildability are the most important, but they are inherently in conflict. Good extrudability requires certain flowability, while good buildability demands a high resistance to flow or deformation. However, for successful AC, both properties shall be achieved at the same time.

d) An appropriate balance of all the constituents shall be reached to ensure proper functioning of the mix. At any time, and depending on the placement environment conditions, this mix proportion is to be re-adjusted to be able to be easily placed in the printer, extruded out consistently, and hold its shape during and after printing:

   1) Flowability of 3D printable material mixtures is assessed by flow table tests and visual inspection. The flow table tests (ASTM C1437 if using cement mortar), and the visual inspection are to be performed to see and feel whether mixtures were easily poured into the extruder of the printer.

   2) Extrudability is evaluated by observing the continuity and uniformity of the extruded filaments of a mixture from the start to end of the AC process.

   3) Buildability is estimated by inspecting slump and distortion of freshly printed objects. When the extruded material does not have enough stiffness or strength to hold the shapes and carry the weight of the layers deposited above, the printed object would slump, deform, or collapse. When any of these occur, the mixture is considered as having unsuitable buildability.

4) Printability is assessed based on the overall result of flowability, extrudability, and buildability. If one of those properties is not fulfilled, an object is considered as lacking in printability.

e) To ensure proper buildability, the mix shall be designed in a way that, after each layer is extruded from the nozzle, it should be able to support its own weight and withstand the subsequent layer with little or no deformation. Low buildability is caused by low yield stress of the materials. High paste content in the mixture could be one of the reasons for low yield stress and this may cause the material to deform under loading and each layer width to be larger than intended.

f) To ensure a proper open time, the target in a mix design is to ensure that each extruded layer has the capacity to hold itself and harden, and yet stay liquid enough to bond with the layer above it and not become a separate entity.

g) Cementitious materials: Percentages of each type of cementitious materials other than Portland cement in concrete shall be determined in a way to suit the required pumpability, buildability, compressive strength, and open time of concrete. Fly ash, geopolymer, slag, and recycled glass are some of the green materials that have been used successfully by the industry, at different rates from conventional concrete cast on site, determined to suit the 3D printing system.

h) Water-Cementitious Ratio: The water-cement ratio shall be determined to suit the 3D printing system, noting that excessive water-cement ratio may lead to segregation, which causes the lubrication layer to be lost, and stops the concrete from moving or clogs the nozzle, and even though low water content attributes to the shape preservation ability of printed layers, however it reduces the pumpability of concrete.

B.6 Material deposition device characteristics

a) Printer: The size of the printer is related to the size of the printable structure; therefore, the design of the printer is to take all applicable criteria into consideration. A team of mobile robots may be used to work collaboratively for the application in large scale AC build, where the dimensions of a structure are beyond the reach of an individual robotic arm or a concise gantry printer. Collision between the robotic arms movement is to be avoided by robot motion planning and coordination.

b) Nozzle: The nozzle diameter has a direct relationship with the material mix properties, specifically its flowability. As the diameter size decreases, the flowability of the mix should be increased to account for it and vice versa. The nozzle size should be designed based on the required/designed width and height of the extruded filament.

B.7 System related pre-processing

a) Ensure that the 3D robot undertakes a start of day (or start of operations) safety protocol in accordance with manufacturer guidelines, and local health and safety regulations.

b) Ensure that material mixing stations, material preparation, water and power supplies are functioning within local tolerances and at the optimum level for quality performance during operations.

c) Ensure that risk assessments are in place and that all operators are suitably equipped to undertake the process.

d) Ensure that foundations for the robot are sufficient for the weight and dynamic load of the robot once in operation.

e) Ensure dynamic loading of the robot has been considered and that safety steps are in place to reduce vibrational movement of the robot whilst in operation (e.g. prevent the robot from moving during operations).

f) Take all necessary steps to safely secure the robot and mitigate against the tipping point of the robotic arm during extension while printing. (e.g. the weight distribution of the arm whilst

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in operation that could cause it to pull the robot over onto one point of the stabilizing legs (less relevant for gantry models).

g) Ensure that all operational instructions are up to date, in place and applied. Operators shall be trained accordingly.

B.8 AC guidelines

a) Verification of conditions:

  1) Before extruding material, verify the position and readiness of the grade slab or substrate, the stability and readiness of the deposition device, the availability of the entire stock of raw material, and all accessories and material needed to maintain the continuous extrusion of material as planned.

  2) Do not proceed until unsatisfactory conditions have been corrected.

b) Building shall not start unless all components are checked and approved, and mix design has proven its conformity with flowability, extrudability, pumpability, printability, buildability, and open time, that are required by the 3D printing system.

c) For the building of overhanging structural elements without changing part orientation, fabrication of support underneath is inevitable using sacrificial material to enable the overhanging segment to be integrated with the main structure instead of connecting modular parts.

  1) Additional supports are to be adopted per structural engineer recommendations.

  2) In case supports are needed, the method to be adopted is to be the more efficient, producing surfaces irregularities within allowed tolerances, and maintaining the continuity and speed of concrete extrusion.

B.9 Combining different materials in AC

Combining different materials in the AC process can optimize structural performance by taking advantage of the unique properties of each material based on the type of loads applied. (For example, using of 3D printed concrete for structural elements under compression while using polymers for elements mainly subjected to tension and/or bending. This type of composite 3D printed structure could be used to create strong and lightweight structures with optimized structural performance.)

In case polymers will be used for building, the design should include all needed information about the polymer material, to allow for adequate analysis and buildability/printability assessment.

Information would include without limitation the following:

a) The material chemical composition and mix in case multiple types of polymers are mixed and used as printing material.

b) The material tensile properties, including the tensile strength, yield strength, and elongation at break in accordance with standards for plastics such as ASTM D638 and standards for polymer matrix composite materials such as ASTM D3039/D3039M.

c) The material compressive properties, including the compressive strength and compressive modulus, in accordance with standards for plastics such as ASTM D695 and standards for polymer matrix composite materials such as ASTM D3410/D3410M.

d) The material shear strength, using testing standard such as ASTM D732 to determine the shear strength of plastics by the punch shear method, ASTM D3165 to determine the shear properties of polymer matrix composite materials by the short-beam method, and ASTM D5379 to determine the shear properties of polymer matrix composite materials by the V-notched beam method.

e) The material ultra-violet weathering effect, including changes in tensile strength, elongation at break, and colour, in accordance with standards for all plastics such as ASTM D4329 or ASTM D5208, noting that the type of polymer being tested would dictate the test method to be used.

f) Chemical, and weather resistance of the material, in accordance with testing standards such as ASTM D543, DELPHI DX900018, ISO 11403-3 or any equivalent testing methods.

g) Fire resistance and density of smoke from burning plastics testing, in accordance with testing standards such as ASTM E84, ASTM D635, and ASTM D2843.

h) External coating may be used for exposed polymer 3D printed objects to enhance material properties and performance, especially UV protection, chemical resistance, weather resistance, fire retarding properties etc.

B.10 Using sensors

Using sensors within a 3D-printed element can provide valuable information about the performance and structural integrity of the element. (For example, sensors embedded within a 3D-printed bridge could be used to monitor stress, strain, temperature, and other factors that could affect the performance of the bridge. This information could be used to optimize future structural design or ensure that the adopted design method is safe and reliable.)

Overall, the use of sensors within 3D printed elements can significantly improve the safety and performance of these structures.

B.11 Default post-processing

a) Ensure that the printer is safely stopped, cleaned and checked for faults after the printing has concluded. Take into consideration any post printing dynamic energy that may remain in the printer arm and act in accordance with local safety regulations.

b) When applicable, ensure that the structure is securely moved and stored to allow for post print strengthening (curing, setting, hardening), which will be informed by local tolerances and standards.

c) Ensure that the baseline data is validated against the building information modelling (BIM) model.

B.12 Element specific post-processing

a) Undertake a physical review of the structure. Checking for defects in the printing. Defects, if any, shall remain within local tolerances. Where the defects are beyond local tolerances, the structure will need to be sustainably assessed and inspected.

b) Quality control of the printed structure shall be performed to meet the established requirements for the printed structure, surfaces, and overall dimensions. In case of non-conformities, the decision shall be taken on a repair with established means and methods or scrap.

c) Undertake a digital review of the model, comparing specifically the centre line, the layer size, number of layers. Where the modelling has highlighted that the structural design is 'close to' partial factors of safety tolerances then it is vital for post-processing to pay specific attention to these areas of the asset.

d) Any specific smoothing requirement of the outer layer of the printed structure shall be undertaken within local tolerances.

e) Any requirement to print an outer façade shall be undertaken within local tolerances.

f) Any requirement to retrofit elements of the structure (e.g. pipe outlets or cable outlets). These processes shall be undertaken at the approved time period to allow post print strengthening

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but mitigate the risk of cracking or damaging of the structure that would reduce the quality, thereafter, creating safety issues with the structure and/or changing the overall functionality. All in conformity with local standards, tolerances and regulations.

g) Specific consideration given to post – printing seismic compliance following local tolerances.

h) Specific consideration given to reinforcement within the structure and its quality, in line with local tolerances.

i) Specific consideration to be given regarding pigmentation, additional materials such as standard 'poured concrete' that could be added to the structure during post processing.

B.13 Logistics

a) Specific consideration given to lifting and transportation of the structure.

b) Quality assurance measures in place for freight travel. Acknowledging local and global road infrastructure and the vibrational impact of road travel on the structure. Consideration to the temporary base and securing of the structure to absorb vibrations created during transportation.

Annex C
(informative)

Examples for quality assurance steps in built process guidance

C.1 General

The contents are presented as a proposed approach for quality assurance in built process guidance and should not be seen as a complete or comprehensive procedure.

C.2 Process guidance

a) Ensure that the base slab for the printing is structurally secure and has localized design standards in place (e.g. the base will withstand vibrational impact of the machine, the dynamic loading of the printer and that there is sufficient space to allow for operators to print within safety zones).

b) Undertake collaboration processes for the printer, ensuring that the mixing station and quality checks on the material are properly conducted.

c) Print a test panel to check and approve quality of the print.

d) Undertake printing process, ensuring consistent mixing and material supply. At pre-determined intervals, ensure that the printed design is being accurately achieved during the process. Ensure that any operator activity such as creating spaces in the printed structure is implemented at the correct time (e.g. cutting out a space for electrical fixtures).

e) Ensure that the layer speed and material consistency are accurate in order to enable correct interlayer bonding.

Ensure that localized tolerances are considered should the printer stop, and need to restart, part way through the structure. Quality assurance measures will need to mitigate any quality, safety or performance issues.

C.3 Layer bonding

Start/Stop procedures (cold joints), ensure strengths meet local standards.

Wetting of printed element (do not wet before material starts to set/harden).

Provide a sheltered printing environment whenever needed.

C.4 After printing considerations

Ensure specimens are stored in suitable environments following local codes and regulations based on the material and element requirements. With each change in material characteristics, samples will need to be taken. Inspection of printed elements for detrimental cracking should also be taken.

a) Foundation for the installation of the printed element shall be designed according to the local area building codes and made according to the established requirements and flatness tolerances.

b) AC element shall pass the required quality control stages for the structural as well as for the usage characteristics before the installation on the foundation.

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c) If required, test specimens of the AC element are printed to confirm that established requirements are met for the structural performance, exterior and interior surface quality (e.g. no gaps between layers), dimensions, etc.

d) If required, ensure that the printing speed and material consistency enable correct interlayer bonding. Meeting established geometry requirements for the AC structure is necessary. Stop/start processes need to be in place.

e) When applicable, produced AC elements shall be safely transported (use packaging if needed) to the place of installation on the prepared foundation. Quality control before the delivery and after delivery shall be performed according to the established requirements.

f) The process of AC element installation shall meet established safety and quality requirements. Proper equipment shall be used to install the AC structure on the foundation.

g) After installation of the AC element, it shall be safely secured.

h) Quality control shall be performed of the installed AC element to confirm that established requirements for the levelling, flatness, evenness are met for the entire AC element.

i) If required joints between AC elements and foundation shall be sealed to meet established requirements for the overall performance of the residential construction.

j) If required coating of the AC element shall be performed according to the established requirements.

Annex D
(informative)

Examples for specific processes

Table D.1 — Section specific process examples for some of the AC solutions/technologies

Section specific examples
6.1 **c)** — *System related maintenance and servicing activities -* Routine calibration for machines. Skipping maintenance of entire AC delivery mechanism including any automated monitoring devices, can result in component failure, flow rate and print inconsistencies, nozzle blockage and more.
6.2 **c)** — *Simulation of Additive Construction processes:* Simulation of Additive Construction processes can be used to increase process stability, thus avoiding build failure.
6.2 **c)** — *Simulation of Additive Construction processes*: Process simulation can be used to increase process stability, thus avoiding build failure by optimizing supports and part orientation. It can also serve to modify (digital) part geometry as to compensate for displacements due to thermal stresses. NOTE The validation plan includes process simulation when applying a pre-deformation to a part.
6.3 — *Requirements for the material management* Geometrical specifications of the printed filament
6.3 **b)** — *Incoming quality control* Conformity of material. Base material does not contain unexpected solid/oversized particles, should be sealed packaging as applicable.
6.3 **b)** — Conformity of material, material does not contain contamination
6.3 **b)** — *Incoming quality control* Newly added mass, blending ratio angle of repose and moisture content, temperature, grain sizes...etc.
6.3 **e)** – *Preparation for process guidance* Process control to consider moisture content
6.4 **b) 1)** — *Slab or base for print* Material (compatibility with temperature and material), cleanliness, surface quality, bearing capacity, flatness
6.4 **b)** — *Setup for production run* Unevenness of the build area, too high temperature gradient (e.g. due to the hydration density) within a build area
6.4 **b) 2) and 9)**— *Setup for production run — Effects in the build space* Coating error or damage to the layer deposition system
6.5 **a) 5)** — *Process parameters* Z-compensation and scaling to compensate for geometrical and process-dependent shrinkage or settlement can be included in the validation plan
6.5 **a) 5)** — Process parameters Speed of the layer deposition system
6.5 **a) 5)** — *Process parameters* Deposition rates, travel paths, fill density
6.5 **a) 5)** — *Process parameters* Incorrect setting of process parameters can lead to part failures: cracking, delamination, high residual stresses, poor surface finish, increased specimen's porosity, lack of fusion, polymerization, bonding or sintering
6.5 **b) 1)** — *Collecting material sample* Retain material samples and check according to the frequency defined in that facility procedure.

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Table D.1 *(continued)*

Section specific examples
6.5 **b)** — *Production run monitoring-* Poor dimensional accuracy, deformation, displacement, shrinkage, undulation, sorting edges, discoloration, surface errors, step formation, higher porosity.
6.6 **b)** — *system clean-up (commissioning)* Optics, support for build platform, material containers, disposal of residues in the build area, complete emptying and cleaning of all material batching, mixing, and delivery systems.
6.6 **b)** — *system clean-up (commissioning)* Pyrometer or FLIR cameras, check layer deposition system's state or change per manufacturing batch.
6.6 **b)** — *system clean-up (commissioning)* Inspection of the extrusion nozzle.
6.6 **e)** — *Application specific post processing* – (where applicable) Haptic or visual limit samples for surface finishing processes: blasting, grinding, polishing, dyeing
7.3 **d) 5)** — *Inspection of process results – Process deviation* Continuous systematic or manual approach with process monitoring feedback or outliers (e.g. one of first 3 monitored layers has a non-conformity, see 6.4

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